All Fiber Mach–Zehnder Interferometer Based on Suspended Twin-Core Fiber

Orlando Frazão, S. F. O. Silva, J. Viegas, José M. Baptista, José L. Santos, Jens Kobelke, and Kay Schuster

***Abstract*—An all fiber Mach–Zehnder interferometer using suspended twin-core fiber is described. Due to the birefringence of the fiber cores, two interferometers are obtained when the fiber is illuminated by a polarized light. Applying curvature or temperature to the sensing head, different sensitivities are observed. In order to discriminate curvature from temperature in the suspended twin-core fiber Mach–Zehnder sensor, the matrix method is used.**

***Index Terms*—Interferometer, microstructured fiber, optical fiber sensor.**

I. INTRODUCTION

THE twin-core fiber was demonstrated as a temperature sensor in 1983 by Meltz *et al.* [1]. The temperature sensitivity of a twin-core fiber sensor with a single cladding and the circular cores is due almost entirely to the linear expansion of the core and the thermo-optic effect. Peng *et al.* [2] fabricated a twin-core optical fiber with large elliptical core with significant polarization-dependent coupling properties. On the other hand, Tjugiarto *et al.* [3] observed that the coupling between the two cores is increased with the spin rate in a spun twin-core fiber. In 2000, Gander *et al.* [4] proposed a two-axis bend measurement using multicore optical fiber. MacPherson *et al.* [5] demonstrated a curvature sensor using a twin-core photonic crystal fiber. Flockhart *et al.* [6] reported two-axis bend measurement using Bragg gratings written in multicore optical fiber.

In this work, the authors propose a new sensing head based on a Mach–Zehnder interferometer (MZI) using a suspended twin-core fiber. This sensing head presents different sensitivity when is subjected to curvature or temperature. The possibility of simultaneous measurement using the matrix method to discriminate curvature and temperature is also demonstrated.

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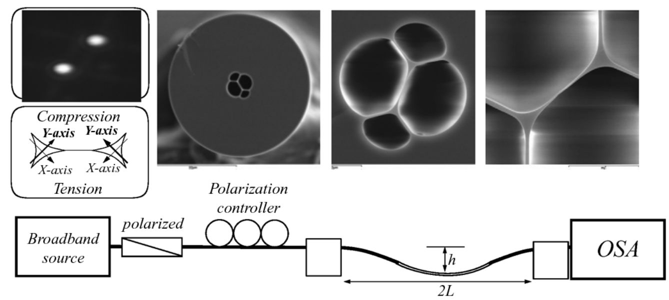

Fig. 1. Experimental setup of the Mach–Zehnder interferometric configuration based on suspended twin-core fiber and photo of the cross-section of the suspended twin-core fiber.

II. EXPERIMENTAL RESULTS

Fig. 1 presents the experimental setup with the sensing head based on a suspended twin-core fiber. Light from a broadband source in the window of 1550 nm is linearly polarized with a polarizer and injected into the suspended twin-core fiber with a length of 0.33 m. A polarization controller was used to induce only rotation of this polarization state. In general, the interferometric fringe pattern observed in the optical spectrum analyzer (OSA) shows an envelope modulation, an indication that there is a beat of interferometric signals. The beat phenomena is not observed for only two orientations of the input polarization state of the light injected into the twin core fiber. The angle between the two field orientations is $\approx 90^\circ$, an indication that in each case the input light is along the eigenaxis of the birefringent fiber cores, which are identified as x and y states in Fig. 1. The fiber cross section and the near-field image of the transmitted light at 1550 nm are shown in the inset of Fig. 1. The suspended twin-core fiber with four holes made of pure silica was fabricated at IPHT (Institute of Photonic Technology, Jena, Germany). The cores diameters are 1.5 μm; the cladding is 124 μm; and the big/small holes are 10/5 μm, respectively. The distance between the two cores is approximately 8.6 μm, where it is possible to illuminate the two cores simultaneously using a standard single-mode fiber (SMF 28). Due to this distance and also considering that the bridge that connects the two cores is very thin, no coupling between the two cores is expected. The splices were made using a conventional splice machine operated in the manual regime that allows us to apply the electric arc (with low current) in the SMF28 side of the junction The coupling efficiency between the SMF28 and the twin core fiber (first splice) is low ($\approx$4%). In the second splice, high efficiency is expected since all the light of the two PCF cores is re-injected in the SMF core in face of their relative dimensions.

A simple curvature sensor can be made using these twin-cores as the two arms of the MZI when light from the optical source is

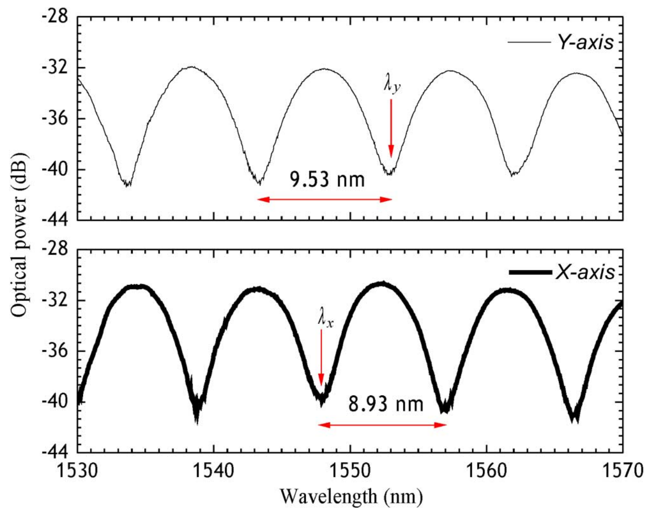

Fig. 2. Spectral response of the interferometric structure for input polarized light along the x- and y-axes.

divided into two beams that propagate along each core and are brought together to form an interferometer. For the curvature sensor, the two cores are positioned as shown in Fig. 1, with the curvature plane in the plane of the figure. Due to the fiber geometry, the triangular core in the suspended twin-core presents birefringence and two discrete MZIs were present. The first interferometer can be obtained when the polarized light excites only the x-polarization state in the two cores. For this polarization state the two cores are in tension. The second interferometer is also obtained when the linear polarized light is along the y-axis, a situation in which the two cores are in compression. Therefore, in these conditions, opposite response of the two interferometers is expected. For the bend tests, a section of suspended twin-core fiber $(2L = 425$ mm$)$ in the middle was clamped between a translation stage and a fixed base. The sensor curvature (C) is given by $C = 1/r = 2d/(h^2 + L^2)$, where h is the bending displacement at the center of the MZI, L is the half distance between the edges of the two clamps, and r is the bending radius [7] (see Fig. 1).

Fig. 2 shows the spectral response of the suspended twin-core fiber MZIs for the two polarization states. From the interference fringe spacing [8], it turns out that the effective refractive index difference for the light propagating in the two cores is 7.6×10^{-4} (x-polarization) and 8.1×10^{-4} (y-polarization). The pattern fringe is analyzed when the suspended twin-core fiber is subjected to curvature; the wavelength spectrum of the interferometer shifts towards higher wavelengths (x-axis) and lower wavelengths (y-axis). The calibration results are shown in Fig. 3(a) (versus curvature radius) and Fig. 3(b) (versus curvature). A linear dependence of the wavelength shift with curvature can be observed, with coefficients of 2.22 nm/m^{-1} (x-polarization) and -2.56 nm/m^{-1} (y-polarization). The interference fringe spacing variation of the MZIs for temperature variation was also characterized. For that, the fiber was placed in an oven where the temperature could be set from room temperature up to 100 °C with an error smaller than 0.1 °C. The results are shown Fig. 4. A decrease of the interference fringe spacing for both polarizations can be observed, with coefficients of -11.4 pm/°C (x-polarization) and -2.7 pm/°C (y-polarization). It is interesting to notice that because this sensing structure operates in a differential mode (phase difference between the light that propagates in the two cores for each polarization), the temperature effect should be common mode, i.e., no effect (or residual) should appear. This was not observed and the reason for that needs further investigation. A root for the explanation shall come from the fact that due to the small dimension of the cores, there is a significant modal evanescent field into the air holes (which is not the same for the x and y polarizations due to the silica bridge between the two cores), connected with a possible different stress state in each core and small geometric asymmetries arising during the fiber fabrication [9]. The observation of the calibration data shown in Figs. 3(b) and 4 indicates the feasibility of using this sensing structure for simultaneous measurement of temperature and curvature. Indeed, if $\Delta\lambda_i$ $(i = x, y)$ are the interference fringe spacing variations of the interferometers for the two polarizations induced by temperature (ΔT) and curvature (ΔC) variations, then it is possible to write the following matrix equation:

$$\begin{bmatrix} \Delta T \\ \Delta C \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{C(x)} & -K_{C(y)} \\ -K_{T(x)} & K_{T(y)} \end{bmatrix} \begin{bmatrix} \Delta\lambda_y \\ \Delta\lambda_x \end{bmatrix} \tag{1}$$

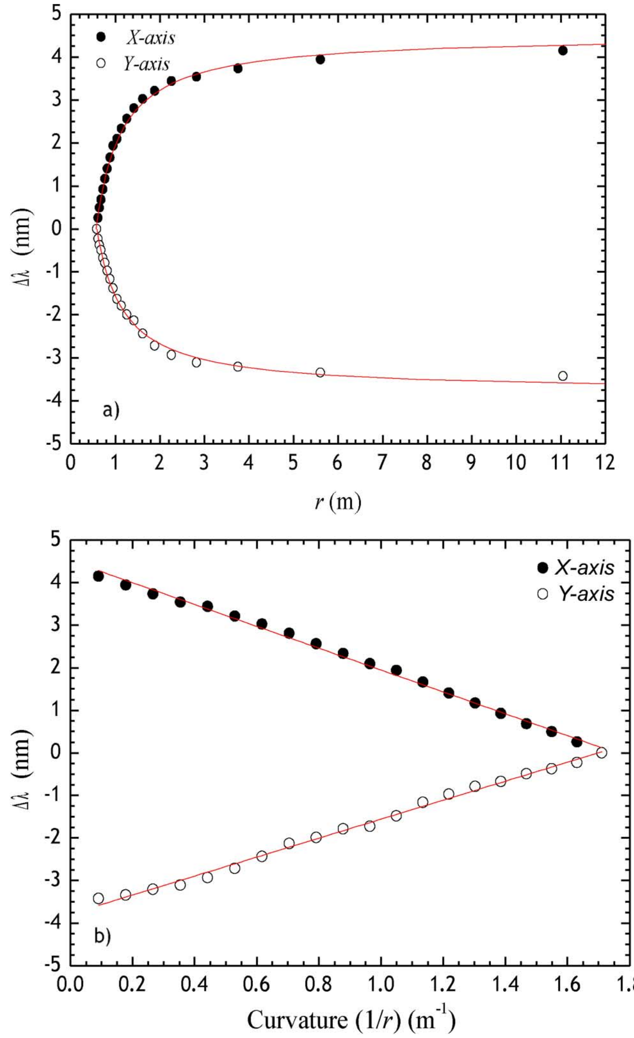

Fig. 3. Spectral relationship of the interference fringe spacing variation $(\Delta\lambda)$ versus: (a) curvature radius; (b) curvature.

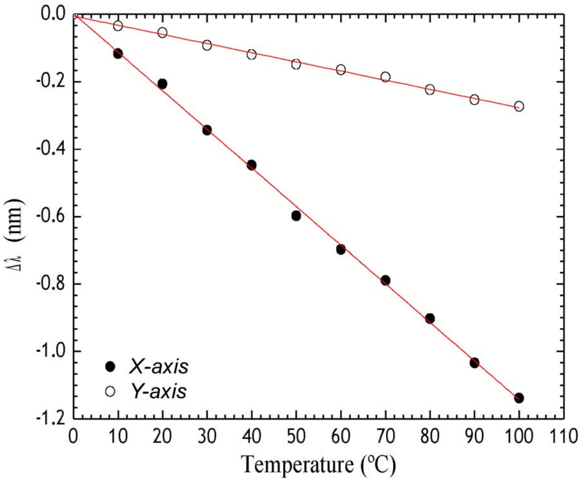

Fig. 4. Temperature response of the MZI for the two polarizations.

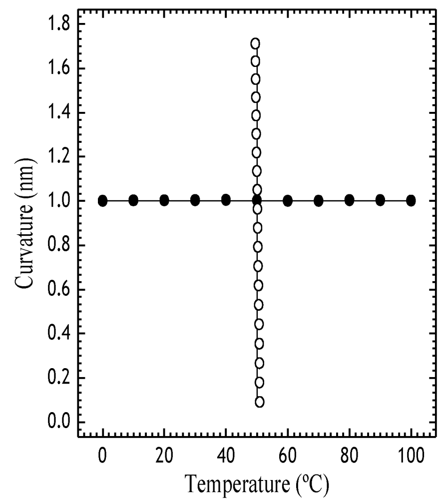

Fig. 5. Sensor output as determined by equation (2) for applied temperature at constant curvature and curvature changing for constant temperature.

where $D = K_{T(y)}K_{C(x)} - K_{C(y)}K_{T(x)}$. Considering the values for the coefficients obtained from Figs. 3(b) and 4, it turns out

$$\begin{bmatrix} \Delta T \\ \Delta C \end{bmatrix} = -\frac{1}{0.035} \begin{bmatrix} 2.22 & 2.56 \\ 0.0114 & -0.0027 \end{bmatrix} \begin{bmatrix} \Delta\lambda_y \\ \Delta\lambda_x \end{bmatrix} \quad (2)$$

where ΔT and ΔC are in degrees centigrade and m^{-1}, respectively, while the wavelengths shifts are in nanometers. The performance of this measurement approach was tested varying the temperature at constant curvature and reciprocally, i.e., varying the curvature at constant temperature. The experimental determination of $\Delta\lambda_y$ and $\Delta\lambda_x$ permitted us to obtain from (2) the measured values for ΔT and ΔC which are compared with the effectively applied ones. The results are shown in Fig. 5, from where it turns out temperature and curvature measurement resolutions of ± 1.5 °C and $\pm 0.01\ \mathrm{m}^{-1}$, respectively.

III. Conclusion

In the present work, it was possible to obtain a new sensing head based on a twin-core fiber that allows us to obtain distinct interferometric signals associated with the two principal linear polarization states of the input light to the sensing head. These signals show substantially different sensitivities to curvature applied to the structure, as well as to temperature variations, a feature that is not present when considering the implementation of a sensing head of this type with standard twin-core fibers. This characteristic permits much higher design flexibility, in particular turns fairly easy to perform with good accuracy simultaneous measurement of curvature and temperature.

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